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Measurements of Wire + Arc additive manufacturing layer heights during arc operation using coherent range-resolved interferometry (CO-RRI)

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Abstract

Wire + arc additive manufacture (WAAM) promises high build rates and is well-suited to the manufacture of large structures. In-process measurements of layer height are critical for WAAM process control but are difficult to achieve due to the presence of bright arc light. In this paper, a novel coherent range-resolved interferometric (CO-RRI) technique is successfully applied to the measurement of layer heights during arc operation in a first step towards gaining full in-process control of deposition layer heights.

In-process measurements, Additive manufacturing, Range-resolved interferometry, Coherent measurements, Optical instrumentation

1. Introduction

Wire + arc additive manufacture (WAAM) [1] is a promising alternative to traditional subtractive manufacturing, particularly for the fabrication of parts from high-value metals such as Titanium. Unlike most additive manufacturing technologies, WAAM offers high build rates (several kg/h) and can use robotic manufacturing cells that have no inherent part size limitations, making it particularly suitable for the manufacture of large components (parts with 6 m length have been demonstrated using WAAM). However, in-process measurements of the layer heights in the bright arc light environment are difficult to achieve using traditional cost-effective distance sensors, such as triangulation or confocal sensors [2]. Furthermore, both triangulation and confocal sensors also require comparatively large sensor heads, making their deployment close to the weld pool difficult. Without suitable layer height measurements, irregular layer profiles can build up over time, compromising part integrity, with this problem being exacerbated in the vicinity of wall joints and other complex part substructures. Here, we propose the use of coherent range-resolved interferometry (CO-RRI) [3] as a technique that permits in-process layer height measurements for WAAM. Achieving layer height measurements at resolutions well below 100 µm and over working ranges above 10 cm using only a compact measurement head (Diameter: 10 mm) makes the CO-RRI technology well suited to the measurement requirements of WAAM. Crucially, as a coherent technique, there is no inherent sensitivity to the arc light, permitting measurements in close proximity to the weld pool. Unlike other existing coherent techniques such as optical coherence tomography (OCT) [4], the proposed technique, while offering lower resolutions than OCT systems, is likely to be considerably more cost-effective due to its simple setup and therefore has the potential to be permanently used on WAAM fabrication cells for online control of deposition layer heights. Also, the much larger working range of the CO-RRI approach allows the seamless acquisition of scans across the full wall profile, where the working ranges above 10 cm offered by the CO-RRI system are much more appropriate for use in WAAM than the sub-cm working ranges typically offered by OCT systems [4]. In this work, we show several example measurements characterising the sensor performance culminating in a layer height measurements over 12 sequential layers on a robotic WAAM cell acquired during welding arc operation. This proof-of-concept experiment acts as a first step towards the ultimate goal of establishing full in-process control of layer heights during the WAAM deposition process and the developed sensing approach should also be relevant to other additive manufacturing techniques.

2. Experimental Setup

The fibre-coupled optical setup of the CO-RRI interrogation unit is shown in Fig. 1(a), where a 5 mW 1550 nm diode laser is sinusoidally wavelength modulated through laser injection current modulation at a modulation frequency of 49 kHz. The light from the laser is guided via a fibre-optic circulator and a single-mode optical fibre lead to a fibre-coupled adjustable lens of ~10 mm diameter that delivers a weakly focused beam to the measurement target. The light returned by the target combines with the Fresnel reflection at the fibre tip in the sensor head, making the system completely down-lead insensitive. The return light is then guided to a photo detector and the resulting interference signals demodulated in the field programmable gate array (FPGA) based signal processing hardware. In the CO-RRI technique [2], to obtain distance measurements, the return signal strength is evaluated as a function of range and a Gaussian peak fit of the return signal peak then yields the desired distance measurement. The original output data is averaged from 49 kHz down to 100 Hz. A photo of the fully-enclosed CO-RRI interrogation unit is shown in Fig. 1(b). The experimental setup at the metal inert gas (MIG) weld head is shown in Fig. 2, where the sensor head is directly mounted on the welding torch. The laser spot is chosen to be 18 mm behind the weld pool centre to assure that the layer height measurement is performed outside the weld pool. Due to geometrical constraints the laser has to hit the weld profile at an angle α of ~8° but even at this angle the return signal

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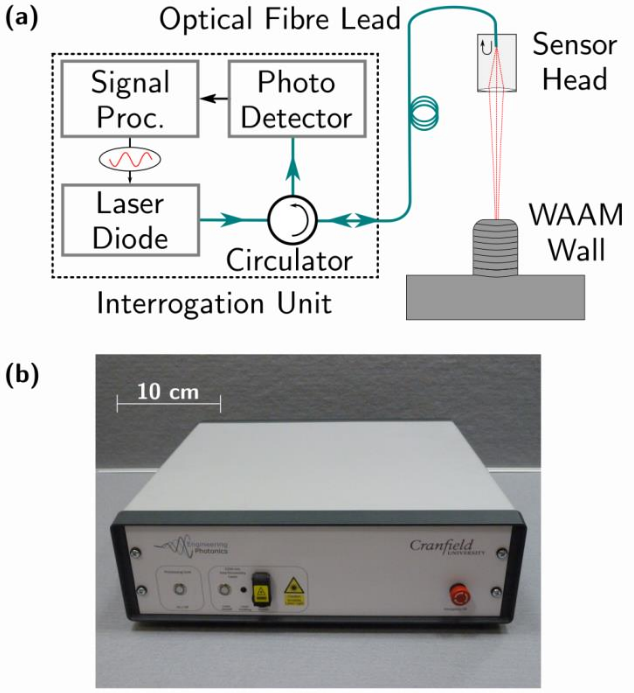

Figure 1. An illustration of the optical measurement setup is drawn in (a) and a picture of the fully-enclosed interrogation unit is shown in (b).

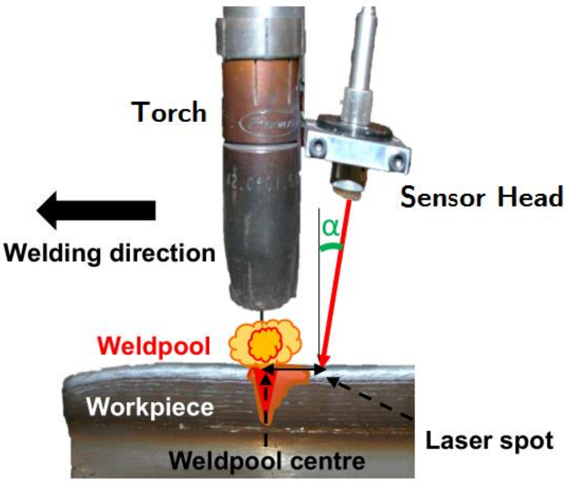

Figure 2. An illustration of the weld head configuration is shown.

strength is generally sufficient for the rough mild steel material used in this work. The weld head was then mounted on an industrial robot that was programmed to perform straight wall builds at a travel speed of ~10 mm/s.

3. Results & Discussion

Initially, to test the general performance of the device, a set of measurements was taken in a separate pass after each layer deposition with the arc light switched off. Fig. 3 shows the height measurements of two sequential layers, layer 3 and layer 4, measured at the top of the wall, with the dotted line showing the moving average over 5 data points. The high data quality is evident, with the initial material build-up at the start of the wall as well as wall height undulations clearly resolved. Fig. 4 then shows a profile scan of the same layers, layer 3 in Fig. 4(a) and layer 4 in Fig. 4(b), where the robot was programmed to move the sensor laterally over the wall, showing that the CO-RRI instrument can also be used to

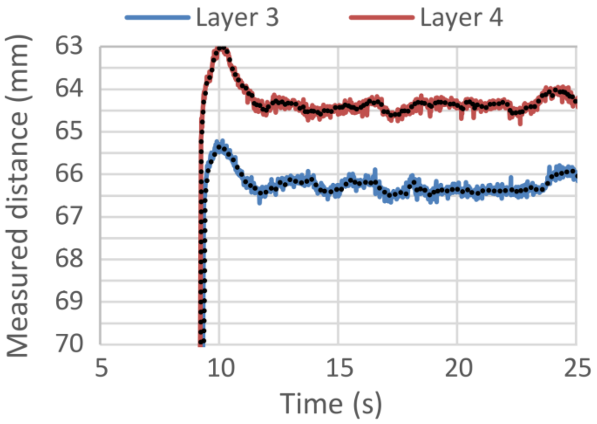

Figure 3. Initial measurement of layers 3 and 4 measured after welding, with a moving average across 5 points represented by the black line.

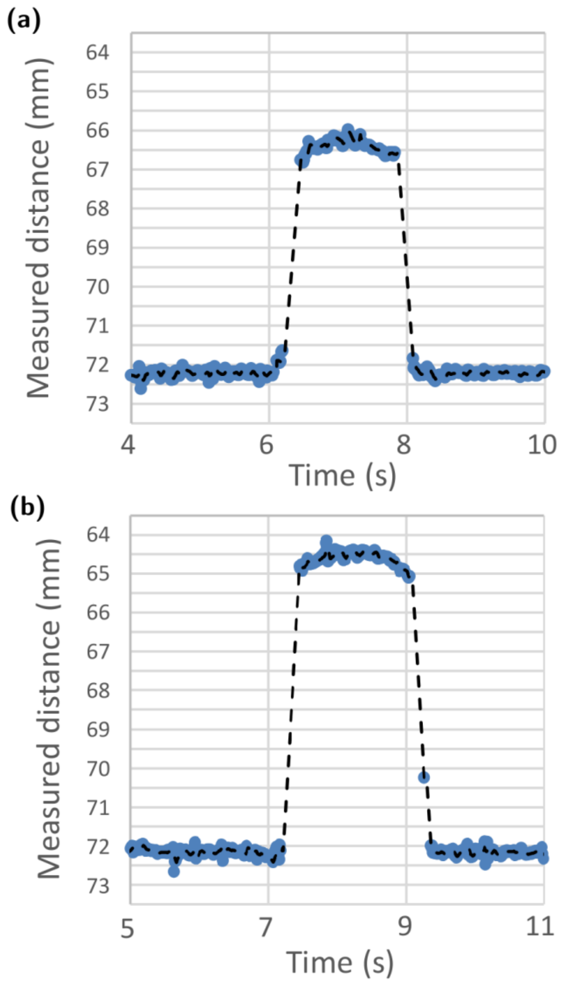

Figure 4. Measured distance across wall profile, layer 3 (a) and layer 4 (b) with a moving average across 5 points represented by the black line.

diagnose the profile of the walls in addition to just measuring the wall height. It can be seen in Fig. 4 that the wall generally has a fairly flat top that should allow meaningful layer height measurements even if the laser spot is not optimally positioned on the centre of the wall.

Measurements with the welding arc operating during wall builds were then performed. As the robot is moved upwards after every layer is deposited to maintain an appropriate distance between the top of the wall and the welding torch, the measurement data had to be referenced to the edge of the build plate, where wall build is not taking place, to obtain

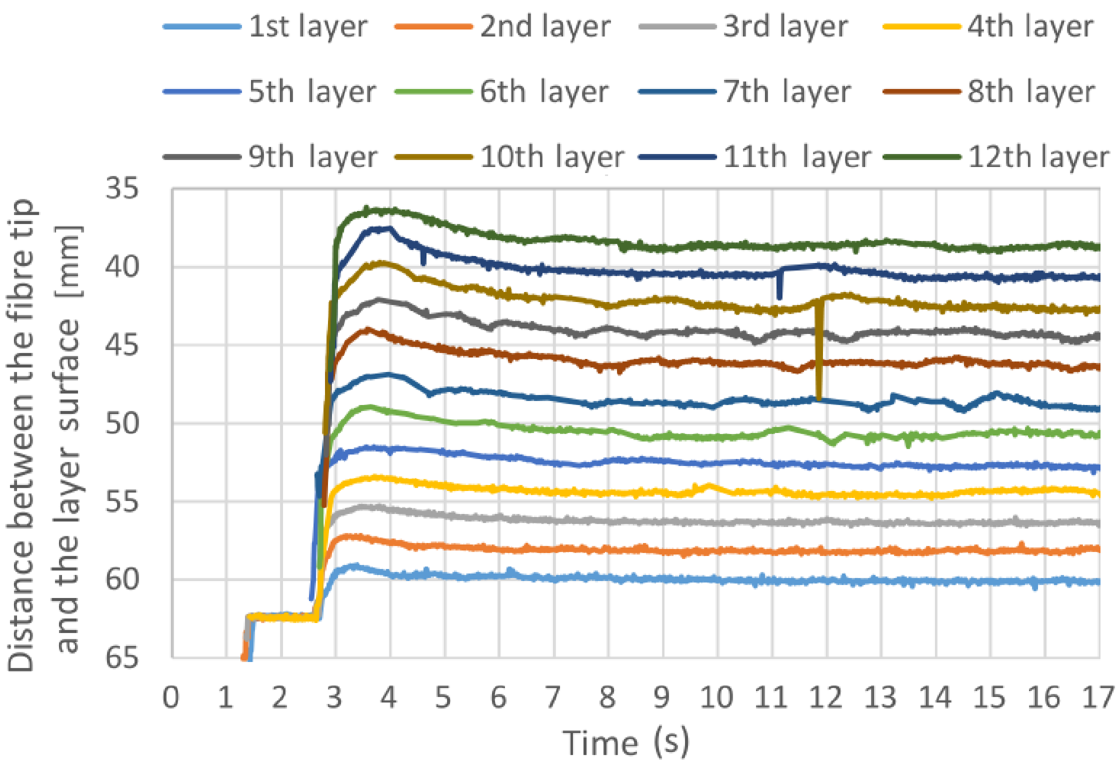

Figure 5. Layer height measurement of 12 sequential layers acquired during welding.

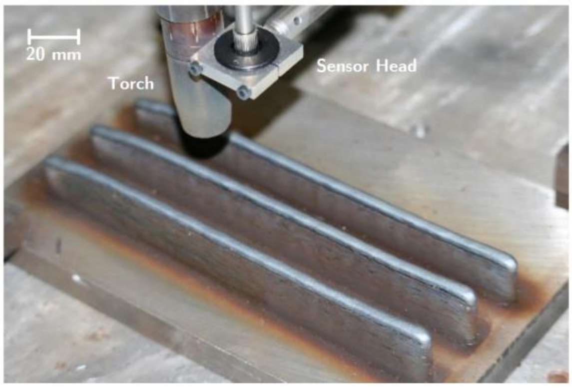

Figure 6. Picture of the three wall builds and the CO-RRI sensor.

correct layer height measurements. Therefore the individual data sets for every layer needed to be shifted so that the measurements from all layers overlap at the chosen origin, the edge of the built plate. This procedure allows the correction of the robot movement and it illustrates the usefulness of the large working ranges that the CO-RRI system provides, because it allows multiple layers to be referenced to the same origin, as each run of the measurement can resolve both the top of the wall and the build plate. Alternatively, the measurement of the robot positional data could have been used for this correction; however, this would then lead to errors in the determination of the robot position to propagate to the critical determination of the WAAM layer heights and is therefore not desirable.

Fig. 5 shows the layer height profiles measured during welding arc operation according to the setup shown in Fig. 2 over 12 sequential layers, with the reference chosen to be the edge of the build plate visible on the left side of Fig. 5. There are isolated instances where the CO-RRI signal exhibits spurious data values and it is thought that these could be removed in future implementations using better spurious signal rejection criteria. It can be seen in Fig. 5 that as the walls are built up, the undulation in the layer height typically increases, showing that there is a strong need for high-quality measurements, such as those provided by the CO-RRI system, to detect layer height irregularities and then, in a second step, provide control signals for corrective action, such as changing the robot travel speed, wire feed rate or welding current in response to the measurement data. Finally, Fig. 6 shows a picture of the three walls on the build plate, with the welding torch and the CO-RRI sensor also shown.

4. Conclusions

We have applied the CO-RRI sensor, a novel coherent optical distance measurement technique, to WAAM layer height measurements. The measurement quality was found to be appropriate for the requirements of the WAAM process and the feasibility of the CO-RRI approach to provide cost-effective sensors for permanent installation on WAAM systems has been established. Future work will investigate full in-process layer height control or apply the CO-RRI sensing approach to other additive manufacturing techniques

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